The Stellar Population and Star Clusters in the Unusual Local Group Galaxy IC 10[1]

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ABSTRACT

We present analysis of *Hubble Space Telescope* U, V, I, and Hα images of the peculiar Local Group irregular galaxy IC 10. The images are used to determine the nature of the stellar products in a portion of the recent starburst in this galaxy. We identified 13 stellar associations and clusters, two of which are probably old ($\geq$350 Myr) and the rest of which are young (4–30 Myr) and presumably formed in the starburst. We found the following: 1) The slope of the stellar initial mass function (IMF) for 6.3–18 $M_\odot$ stars formed in the starburst lies between two limiting cases: a value of -1.9 ± 0.4 under the assumption of coevality over the past 13 Myr and of -0.9 ± 0.3 under the assumption of constant star formation over the past 40 Myr for $Z = 0.004$ (-2.1 ± 0.4 and -1.0 ± 0.04, respectively, for $Z = 0.008$). Thus, most likely, the IMF of the intermediate mass stars is not very unusual. The slope of the IMF for the underlying galaxy population under the assumption of constant star formation is -2.6 ± 0.3 for 4.8–18 $M_\odot$ stars assuming $Z = 0.004$ (-2.3 ± 0.3 for $Z = 0.008$), and is unusually steep. 2) The lower stellar mass limit in the starburst is ≤ 6.3 $M_\odot$. This constraint is less than some predictions of what lower stellar mass limits might be in starbursts, but higher than others. 3) There are two modest-sized Hα shells ($\sim$50 pc diameter) that could easily have been produced in the past few Myr by the clusters they encircle. 4) The dominant mode of star formation in the starburst has been that of a scaled-up OB association. This mode, with a few compact clusters sprinkled in, is similar to the star formation that took place in Constellation III in the LMC, as well as that in the Blue Compact Dwarfs IZw18 and VIIZw403. The starburst in this part of IC 10 has not produced a super star cluster. We also compare the high WC/WN ratio to evolutionary models and discuss possible explanations. The high ratio can be reproduced if there were small, well-synchronized ($\Delta\tau \leq 1$ Myr), but widely scattered, pockets of secondary star formation 3–4 Myr ago.

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1. Introduction

IC 10 is a small irregular galaxy in the Local Group. With an M_B of −16.5, IC 10 has an integrated luminosity that is comparble to that of the SMC (although IC 10 is 0.2 magnitude redder in $(B-V)_0$ and the same in $(U-B)_0$; de Vaucouleurs et al. 1991). What is unusual about IC 10 is that it is undergoing a wide-spread burst of star formation, according to a study of the massive stars by Massey & Armandroff (1995). Massey & Johnson (1998) found that the density of evolved massive stars in the Wolf-Rayet phase is several times higher than that of the LMC, but the LMC is 4 times more luminous than IC 10. The integrated star formation rate for IC 10 inferred from the Hα luminosity is 0.03 $M_\odot$ yr^{-1} kpc^{-2} and is high compared to most other irregular galaxies (Hunter 1997). (Note: The rate derived by Borissova et al. (2000) from Hα and Brγ imges, normalized to the area of the galaxy is 8 times higher than this value, primarily due to higher extinction corrections used).

IC 10 is also known to be unusual in having H I gas that extends about 7 times the optical dimensions of the galaxy (Huchtmeier 1979). Furthermore, that extended gas contains a large H I cloud (Wilcots & Miller 1998), which it has been suggested is falling into the galaxy causing the current heightened star formation activity (Saitō et al. 1992). At a distance of ∼0.5—1 Mpc (Massey & Armandroff 1995; Saha et al. 1996; Wilson et al. 1996; Sakai, Madore, & Freedman 1999; Borissova et al. 2000), IC 10 is the nearest example of the starburst phenomenum. As such, it offers a unique opportunity to test ideas about the star formation process in a starburst environment by examining the products of the starburst event.

In studies of a few starburst galaxies, some people have come to the conclusion that lower mass stars must not have formed in the recent round of intense star formation in those systems (Scalo 1987, 1990). In M 82, for example, Rieke et al. (1993) and Doane & Mathews (1993) argue for a deficit of stars of mass less than a few $M_\odot$. Another interacting system (Mrk 171,IC 694) and a Blue Compact Dwarf (Tol 65) may have formed only O or early B stars (Augarde & Lequeux 1985, Olofsson 1989), and a third interacting system is believed to have a lower mass limit, M_l, of 3–6 $M_\odot$ (Wright et al. 1988).

Unfortunately, because these galaxies are at large distances, individual stars cannot be resolved and the arguments for high M_l's have necessarily been indirect and, therefore, highly uncertain. In fact Scalo (1990) reviews the evidence for unusually high M_l's and concludes that many starburst galaxies do not seem to require a top-heavy stellar initial mass function (IMF). Furthermore, in R136, the super star cluster in the LMC, where star formation has been *locally* intense, the stellar IMF is normal down to at least 3 $M_\odot$ (Hunter et al. 1995, Sirianni et al. 2000)

although massive star clusters near the Galactic center *do* appear to have an unusually shallow IMF for stars with masses greater than 10 $M_\odot$ (Figer et al. 1999). The case for a top-heavy IMF in *some* systems is hard to dismiss.

Theoretical arguments also bolster the expectation that M_l could be unusually high in environments of intense star formation, even in regions of galaxies that are only locally intense. For example, Silk (1977) and Larson (1985) have suggested that massive stars form in hotter, more turbulent environments than do lower mass stars. Therefore, Güsten & Mezger (1983) concluded that M_l >2–3 $M_\odot$ in spiral arms, and Silk (1986) has suggested that M_l could be as high as 10 $M_\odot$ in giant H II regions.

People have long been suspicious that not only is M_l unusual in a starburst, but that the proportions of stars that are formed are unusual as well. In IC 10, Massey & Armandroff (1995) found an unusually large ratio of the evolved massive Wolf-Rayet WC-type to WN-type stars for this galaxy, a ratio that is 20 times too high for its metallicity (Massey 1999). They suggested that IC 10 may have an IMF that is skewed towards the highest mass stars, which they blamed on the very vigorous star formation occurring there now.

Besides the proportions and mass limits of the stars, the nature of the star clusters formed in a starburst is also a clue to the conditions for star formation that were endemic during the burst. For example, some starbursts in small galaxies have produced super star clusters— young, compact, luminous clusters, many of which may be as massive as globular clusters in the Milky Way. These include the irregulars NGC 1569, NGC 1705, and NGC 4449 (Meurer et al. 1992; O'Connell, Gallagher, & Hunter 1994; Ho & Filippenko 1996; Gelatt, Hunter, & Gallagher 2001), as well as the giant star-forming event 30 Doradus in the LMC (Hunter et al. 1995) and several embedded sources inferred to be super star clusters (NGC 2363 in NGC 2366—Drissen et al. 2000; He2-10—Conti & Vacca 1994, Kobulnicky & Johnson 1999; NGC 4214—Leitherer et al. 1996; NGC 5253—Turner, Ho, & Beck 1998). Other starbursts, however, have not produced super star clusters (IZw18—Hunter & Thronson 1995; VIIZw403—Lynds et al. 1998). Thus, we would like to know what kinds of star clusters have been produced in the recent starburst in IC 10.

Because of its relatively close proximity, therefore, we chose to use IC 10 as a test for star formation processes in a starburst galaxy. Towards this end, we obtained *Hubble Space Telescope* (*HST*) images of IC 10 through three broad-band filters that simulate U, V, and I and a narrow-band Hα filter. These data allow us to examine the products of the star formation process, particulary the intermediate mass stars and star clusters. We are addressing the questions: 1) What is the stellar IMF of the intermediate mass stars produced in the starburst? 2) What is the lower stellar mass limit of stars produced in the recent starburst? 3) What kinds of star clusters have been produced in the starburst? 4) How does the nebular emission relate to the stellar products? 5) What has been the mode of star formation in the starburst? In a subsequent paper we will examine constraints on the galactic star formation history from the color-magnitude diagram of the stellar population.

2. Observations and Data Reduction

IC 10 was imaged with the Wide Field and Planetary Camera 2 (WFPC2) on *HST* in two sessions. Observations through filters F336W and F814W were obtained on 1997 June 8, and observations through filters F555W and F656N were obtained at the same orientation on 1999 June 9 and 10. The WFPC2 camera consists of a PC CCD with a resolution of 0.0456″ per pixel, which is 0.22 pc at the galaxy, and three WF CCDs with a resolution of 0.0996″ per pixel, which is 0.48 pc at the galaxy. We obtained three 800 s exposures through each of filters F336W and F656N and 10 1400 s exposures through each of filters F555W and F814W. The multiple exposures were combined to remove cosmic rays but conserve flux.

Basic data reduction steps were done by the Space Telescope Science Institute "pipeline" processing system. We produced a nebular emission image by combining the F555W and F814W images, shifting, scaling, and subtracting from the F656N image to remove the stellar continuum. We also produced nebular-free F555W and F814W images by scaling and subtracting the nebular emission image. The field of view of the *HST* images is shown superposed on a ground-based image of IC 10 in Figure 1.

We measured the brightnesses of stars in the galaxy using the crowded star photometry package HSTphot, designed by Dolphin (2000a) after DAOPHOT (Stetson 1987) but optimized for WFPC2 images. Stars were eliminated if they had high χ and deviant sharpness parameters, measures of the shape of the object relative to the input point-spread-function. The photometry was corrected for the Charge Transfer Efficiency problem that causes some signal to be lost when charge is transferred down the chip during readout. This problem affects objects at higher row numbers more than those at lower row numbers and is a function of time elapsed since WFPC2 was installed. We used the formulism for correcting for this problem and the calibration parameters given by Dolphin (2000b). We also converted the F336W, F555W, and F814W photometry to the Johnson U and V and Kron-Cousins I systems using the conversions of Dolphin (2000b), which are minor adjustments to the original calibration by Holtzman et al. (1995). The instrumental magnitudes were corrected for reddening and the red leak in F336W, as discussed below, before converting to U, V, and I, as discussed by Holtzman et al. We required that stars be successfully measured in both F555W and F814W to be retained, and the final photometry list contains 44241 stars.

We also used ground-based V and R-band images of IC 10 given to us by P. Massey. The images were taken in 1992 at Kitt Peak National Observatory with the 4 m telescope and a Tektronix 2048×2048 CCD. There were two exposures of 500 s each. The field of view was 14.3′.

3. Data Analysis Issues

3.1. Reddening

IC 10 lies in the plane of the Milky Way and so is highly reddened from foreground extinction. In addition there is likely to be some internal reddening within IC 10. Estimates of the total reddening $E(B-V)_t$ to and within IC 10 have varied greatly. De Vaucouleurs & Ables (1965) used integrated U, B, and V colors of the galaxy to estimate $E(B-V)_t$ at 0.87. Lequeux et al. (1979) measured the Balmer decrement from emission-line spectroscopy to derive a reddening of 0.47. Yang & Skillman (1993) used the ratio of Hα to radio continuum fluxes in two H II regions to find $E(B-V)_t$ of 1.7–2. Massey & Armandroff (1995) estimate the reddening at 0.75–0.80 from Wolf-Rayet (WR) stars and from a comparison of the blue main sequence to that of the LMC. Saha et al. (1996) determined an $E(B-V)_t$ of 0.94 from the blue limit for unevolved supergiants. Wilson et al. (1996) determined the reddening at 0.8 from near-infrared observations of Cepheids. Sakai et al. (1999) also analyzed near-infrared observations of a few Cepheids along with V,I photometry of others to conclude that $E(B-V)_t = 1.16 \pm 0.08$. Borissova et al. (2000) compare JHK photometry of red supergiants in IC 10 to those in IC 1613 and derive $E(B-V)_t = 1.05 \pm 0.10$, with higher extinction to H II regions. The compilation of Schlegel, Finkbeiner, & Davis (1998) used to map dust in the Milky Way concludes that the *foreground* reddening at the position of IC 10 is 1.6 in E(B−V). Thus, estimates of $E(B-V)_t$ for the stars in IC 10 range from 0.5 to somewhat greater than 1.6 magnitudes.

We began by adopting an $E(B-V)_t$ of 0.77 from Massey & Armandroff (1995), and dereddened the stellar photometry using this. In the U, V, and I color-magnitude diagrams (CMDs) of the burst region and of individual star clusters (presented in §4.1.1), we found that isochrones fall along the blue edge of the blue plume as expected. The agreement between the model main sequence and the observed photometry is quite good, suggesting that E(B−V)'s much higher than 0.77 would not be reasonable. In particular, an $E(B-V)_t$ of 1.6 magnitude would require that the blue plume and blue luminous cluster stars have a $(V-I)_0 \sim -1.3$ and $(U-V)_0 \sim -2.9$, which are unphysical. An $E(B-V)_t \sim 1$, as found by several authors, would move the middle of the blue plume 0.1 magnitude and the blue edge 0.3 magnitude blueward of the isochrones in $(V-I)_0$ and similarly in $(U-V)_0$. The stars in the resolved clusters would also fall blueward of the isochrones in the CMDs. Thus, while there is certainly some uncertainty in the reddening adopted here, an overall reddening of the stars in IC 10 as high as 1.0 magnitude in $E(B-V)_t$ is inconsistent with our photometry. However, an additional E(B−V) of order 0.05 magnitude would bring the isochrones to the middle of the blue plume and the red supergiants more in line with the ends of isochrones (but see discusssion in §4.1.1), and so a somewhat higher $E(B-V)_t$ cannot be ruled out.

However, the main sequence does have breadth to it, of order 0.5 magnitude in $(V-I)_0$ and 0.7 magnitude in $(U-V)_0$. Some of this must be evolution of the stars, as well as the presence of binary stars and stellar rotation, but could there be significant *variable* reddening within the field of view of the WFPC2? Massey & Armandroff (1995) examined this issue by looking at the reddenings determined from WR stars. They divided the WR stars into two groups—one group lying at high HI column densities, and the other at lower column densities. The higher HI column

densities might imply a higher reddening as well. They found a reddening of 0.73±0.08 for one group and 0.87±0.05 for the other group. Thus, a variation of order 0.1 in E(B−V) is possible. Yang & Skillman (1993) found a difference in E(B−V) of 0.3 between two H II regions from radio continuum and Hα observations as did Borissova et al. (2000). However, one would expect the reddenings within nebulae to be higher and more variable than that experienced by unembedded stars. We conclude that some differential reddening probably is occurring. One might expect this in particular in regions of residual nebulosity. However, if some stars are reddened more than our adopted value by <0.1 magnitude, the error in $(V-I)_0$ is of order <0.1. We have, therefore, adopted the single $E(B-V)_t$ value of 0.77 for all stars, but recognize that some scatter in the CMDs could be due to differential reddening.

Holtzman et al. (1995) showed that the reddening correction in the WFPC2 filters is a function of the spectrum of the object (see also Grebel & Roberts 1995), and in F336W the difference between the extinction of an O6 star and a K5 star can be large. Since the colors of the stars cover a large range, we have determined a reddening correction that depends on the observed F555W−F814W color of the star. For stars with F555W−F814W<1.25, we used the corrections appropriate for a blue star (Holtzman et al.'s O6 star; $A_{336} = 3.935$, $A_{555} = 2.482$, and $A_{814} = 1.472$); for stars with F555W−F814W>2, we used the corrections appropriate for a red star (Holtzman et al.'s K5 star; $A_{336} = 2.932$, $A_{555} = 2.338$, and $A_{814} = 1.412$); and for stars in between these two colors we used an average of the O6 and K5 corrections. Our use of these three distinct color bins results in the two gaps in $(V-I)_0$ visible in the CMDs. We followed this same proceedure for correcting the integrated colors of star clusters as well.

3.2. Distance

Distance estimates to IC 10 have varied as widely as have reddening estimates. In their study of WR stars in IC 10, Massey & Armandroff (1995) derived an $(m-M)_0$ of 24.9. Saha et al. (1996) derived a distance modulus of 24.59±0.30 from optical observations of Cepheids. Wilson et al. (1996) concluded that $(m-M)_0$ is 24.57±0.21 from near-infrared observations of Cepheids. Sakai et al. (1999) use V,I and near-infrared photometry of Cepheids to derive a distance of 660±66 kpc and the tip of the red giant branch (TRGB) to obtain a lower limit to the distance of 500 kpc. Borissova et al. (2000) used red supergiants to obtain a distance of 590±35 kpc.

With the stellar photometry corrected for reddening as described in the previous section, we have estimated the distance to IC 10 from the TRGB following the method outlined by Lee, Freedman, & Madore (1993). In this method $m-M=I_{TRGB}+BC_I-M_{Bol,TRGB}$, where I_{TRGB} is the apparent I-band magnitude of the TRGB determined from a break in the I-band luminosity function, BC_I is the bolometric correction to the I-band luminosity of the TRGB, and $M_{Bol,TRGB}$ is the bolometric I-band luminosity of the TRGB. BC_I is a function of $(V-I)_{TRGB}$, and $M_{Bol,TRGB}$ is a function of $(V-I)_{-3.5}$, which is (V−I) at M_I=−3.5. The I_0 versus $(V-I)_0$ CMD is shown in Figure 2. Stars to the right of the dashed line were taken to be red giant branch (RGB) and

asymptotic giant branch (AGB) stars and included in the I-band luminosity function (see, for example, Lee 1993). We included only stars located outside the burst region and corrected for foreground stars and incompleteness, as described below.

The I-band luminosity function is shown in Figure 3. The TRGB is characterized by an abrupt change in star counts in this luminosity function. Various examples for other irregulars are shown by Lee et al. (1993), and this method was applied to IC 10 by Sakai et al. (1999) using ground-based data. In Figure 3 there is no overwhelmingly obvious break. From the appearance of the CMD we expect that the TRGB lies somewhere between 20.5 and 21 magnitudes. There is a small jump at 20.8 magnitudes. If this represents the TRGB, then $(V-I)_{TRGB} = 1.74$, $(V-I)_{-3.5} = 1.8$, and $(m-M)_0$ is 24.95±0.2. The uncertainty is simply taken to be the width of our luminosity bins. The distance modulus obtained by Sakai et al. (1999) from the TRGB is 24.1, corrected to an E(B−V) of 0.77 used here. Thus, their distance is 0.9 magnitude or 290 kpc closer. However, they consider their TRGB distance to be a lower limit because of reddening uncertainties.

Thus, having adopted the reddening of Massey & Armandroff (1995), we have recovered the distance that they determined as well. A different choice of extinction would result in a different distance, but we have shown in §3.1 that a choice of $E(B-V)_t$ that is much higher leads to unphysical stellar colors. Therefore, here we use the combination of $E(B-V)_t$=0.77 and $(m-M)_0$=24.9 (D=0.95 Mpc).

3.3. Red Leak in F336W

We have corrected the F336W photometry for the red leak in that filter. This is particularly important for objects in IC 10 which are highly reddened from foreground extinction. To determine the red leak as a function of the observed F555W−F814W color, we used the simulations in STSDAS and blackbody curves reddened by a total $E(B-V)_t$ of 0.77. The red leak was taken to be any flux contribution from wavelengths ≥4000 Å, after the definition of Holtzman et al. (1995). The F336W stellar photometry was corrected for the red leak based on its observed F555W−F814W color. For a red star with an observed F555W−F814W of 2, the contribution of the red leak to the F336W magnitude is 0.19 magnitude. The correction increases rapidly for redder observed colors, but the reddest stars were also too faint in U to detect in F336W. All but a few stars detected in F336W have F555W−F814W≤2. The large scatter in $(U-V)_0$ for fainter stars in V,U−V CMDs, shown below, suggests that the red leak correction has not been totally successful for stars that are faint in the F336W image.

3.4. Star Count Incompleteness Corrections

We estimated incompleteness factors in the F555W and F814W images as a function of magnitude and F555W−F814W color by adding 35 million artificial stars one at a time to the images. Using HSTphot, we added the artificial stars, reran the photometry and extraction proceedures as we had originally, and determined what stars were recovered and at what magnitude they were measured. Stars were added according to the original numbers and distributions of stars on the F555W images. We required that a star be recovered on both F555W and F814W images. We used these data to determine incompleteness corrections for each region, color bin, and magnitude bin in which we were counting stars. Since the incompleteness corrections are determined for each region, CCD chip, and color and magnitude binning used in the following calculations, we cannot present all corrections here. However, in Figure 4 we present a representative sample of incompleteness corrections used below.

3.5. Subtraction of Foreground and Underlying Stellar Populations

Because IC 10 is located at low Galactic latitude, there is a considerable foreground star population that must be removed at least statistically. We have used the Bahcall-Soneira model of the Galaxy (Bahcall & Soneira 1980) to estimate the contribution from the Milky Way at the position of IC 10 as a function of V magnitude and V−I color. We transformed B−V in the model program to the Kron-Cousins V−I using the assumption that the luminosity class of the stars is V or III (not I) as indicated by the model itself. The authors suggest 25% uncertainties in predicting star counts, but also warn of increased uncertainties for $b < 10°$. IC 10 is at a b of $-3.3°$, and thus, the model results are uncertain. The model predicted the number of stars per unit area in different color bins for V magnitudes of 18 to 28.

To check the model, we used the ground-based images of IC 10 provided by P. Massey to estimate the contribution of stars in the Milky Way to the star counts of IC 10. We measured the V-band brightnesses and V−R colors of the stars outside IC 10 (beyond a radius of $5.6'$ centered on IC 10), determined incompleteness corrections, constructed a corrected luminosity function, and converted V−R to V−I. The ground-based image covers only V magnitudes to 22; fainter than that incompleteness factors exceed 50%. However, in the brighter 3.5 magnitudes that we measured, the results from the ground-based images and predictions from the Bahcall-Soneira model agree very well.

Therefore, when we wished to examine the entire galaxy population or the underlying galaxy population, we used the Bahcall-Soneira model predictions to subtract the foreground stellar population. However, when we wished to isolate the recent starburst, we used the *HST* images themselves to subtract the underlying galaxy population as well as foreground stars. We did this by identifying the region not included in the starburst, mostly WF2 and WF3; counting stars; correcting for incompleteness; scaling by the relative areas of the chips; and subtracting the

numbers in the underlying galaxy from those in the burst region. This assumes that the burst region has undergone the same star formation history as the region outside of that until the burst began.

4. Stellar Initial Mass Function

The stellar mass function is the number of stars *counted* as a function of the mass of the star. The stellar *initial* mass function, or IMF, is the number of stars *formed* as a function of the mass of the star. Obviously, it is the IMF that we want to determine in order to probe the star formation process. We assume that the mass function is a power law, $f(m) = Am^{\gamma}$, in the notation of Scalo (1986). Then $\xi(\log m) = (\ln 10) m f(m)$ and $\Gamma = \frac{\partial \log \xi(\log m)}{\partial \log m}|_m$, where $\gamma = \Gamma - 1$. The slope of the IMF that we measure is Γ, and for a Salpeter (1955) IMF, Γ is -1.3.

For a coeval population that is younger than the lifetimes of the stars being considered, the IMF is constructed by counting the number of stars in mass bins and dividing by the difference between the logarithm of the mass that brackets the upper end of the bin and the logarithm of the mass that brackets the lower end of the bin. The mass bins are chosen to be approximately equal in this difference. One often then divides by the area of the galaxy being surveyed although we will not do that here since it does not affect the power law index. The power law index, refered to as the "slope" of the IMF, is then the slope Γ of the best linear fit to the logarithm of the number of stars per mass bin ξ versus the logarithm of the average stellar mass of the bin. We take the uncertainty in ξ as the root-N statistics of the number of stars counted, and the uncertainty in Γ as the uncertainty in the linear fit to $\log \xi$ versus $\log m$.

If a stellar population is not coeval, one must consider the star formation history of the region. In the case where star formation has been constant, for stars with hydrogen-burning lifetimes that are less than the age of the region, Scalo (1986) shows that $\xi(\log m) = \frac{\phi_{ms}(\log m) T_0}{\tau_{ms}(m) b(T_0)}$, where $\phi_{ms}(\log m)$ is the present-day mass function determined from the luminosity function of main sequence stars, T_0 is the age since star formation began in the region, $\tau_{ms}(m)$ is the hydrogen-burning lifetime of a star of mass m, and $b(T_0)$ is the birthrate at T_0 relative to the average over the region's lifetime. This assumes that the IMF has been independent of time. The ratio $T_0/\tau_{ms}(m)b(T_0)$ serves to scale the number of stars counted today in order to correct for stars now dead, and if we assume that $b(T_0) = 1$, that is, a constant star formation rate, the scaling factor is just the ratio of the age of the region to the hydrogen-burning lifetime of the stars. Thus, since T_0 is a constant, the effect of assuming constant star formation is to divide the coeval mass function by the hydrogen-burning lifetimes of the stars in each mass bin.

In what follows, we have used the isochrones and stellar evolutionary tracks compiled by Lejeune & Schaerer (2001). The oxygen abundance in IC 10, determined from H II regions, is measured at log(O/H)+12 = 8.26 (Garnett 1990), which implies a Z of 0.005. We, therefore, use isochrones and stellar evolutionary tracks for metallicities of $Z = 0.004$ and $Z = 0.008$. The

stellar hydrogen-burning lifetimes, time-weighted average M_V, and U, V, and I isochrones were determined or taken from Lejeune and Schaerer's basic models with standard stellar mass-loss.

4.1. Starburst Region

4.1.1. Color-magnitude Diagrams

Because we wish to determine whether the stellar IMF or stellar lower mass limits were unusual during the recent starburst, we have isolated the portion of the galaxy in the *HST* field-of-view that appears to have taken part in this starburst. We drew a boundary around this region by looking for the portion of the field-of-view that is higher in surface brightness than its surroundings and where there is a higher density of bright, blue stars. The region thus chosen is outlined in Figure 5. The underlying galaxy was taken to be the regions not included in the starburst. A dark cloud in WF4 was excluded from consideration in either category and is outlined with a box in Figure 5. The starburst is located primarily in PC1 and WF4, with small pieces in WF2 and WF3. The region contains an area equivalent to a square 425 pc on a side.

Color-magnitude diagrams of stars in the burst region and in the underlying galaxy are shown in Figures 6 and 7. Superposed are isochrones for $Z = 0.004$ metallicity from Lejeune & Schaerer (2001). The zero age main sequence of the isochrones falls along the blue edge of the blue plume, as expected. In the CMD of the starburst region we see that the red extension of the isochrones to the red supergiants falls of order 0.1—0.2 magnitude in $(V-I)_0$ short of many of the observed stars. We use $Z = 0.004$ stellar evolutionary tracks because this metallicity is close to the oxygen abundance determined for IC 10 from nebular emission. However, the more metal-rich $Z = 0.008$ isochrones extend further to the red than $Z = 0.004$ isochrones and so encompass the observed red supergiants without changing significantly the blue main sequence. In §7.2 we will also find that $Z = 0.008$ cluster evolutionary tracks (derived from the same stellar evolutionary tracks) better match the observed integrated colors of star clusters in IC 10. Since the oxygen abundance in IC 10 implies $Z = 0.005$, one would expect the $Z = 0.004$ tracks to be a little too metal-poor, and probably the best fit would be tracks between $Z = 0.004$ and $Z = 0.008$. Thus, we have calculated the stellar IMFs in IC 10 using both $Z = 0.004$ and $Z = 0.008$ stellar evolutionary tracks. However, this mismatch of observed Z and evolutionary tracks is not unique to IC 10; the same issue arose in studies of clusters in two other metal-poor irregulars— NGC 1569 (Hunter et al. 2000) and NGC 4449 (Gelatt, Hunter, & Gallagher 2001) where higher metallicity cluster evolutionary tracks fit observed cluster colors better.

4.1.2. The Stellar IMFs

Although a starburst represents an unusually high star formation rate over a short period of time, it is not clear whether this starburst took place over a short enough period of time to be considered coeval or whether it must be considered constant star formation over some extended time interval. By coeval, we mean that the duration of the event is less than the hydrogen-burning lifetimes of the most massive stars being considered, here 11 Myr for 18 $M_\odot$ or 13 Myr for the lifetime of the average mass in the top mass bin. The CMD suggests that star formation may have continued over a period of several tens of millions of years, extending to as recent as 4 Myr ago, but the WR data may suggest that star formation took place over a very short period of time. Because of the uncertainty of how the starburst proceeded, we have determined the IMF for the two limiting extremes: coeval and constant star formation. These IMFs should bracket the true IMF if the star formation history during the burst was more complex.

We have determined the IMF in 4 mass bins from 6.3 $M_\odot$ to 18 $M_\odot$. The masses of stars more massive than 18 $M_\odot$ cannot be determined from photometry alone (Massey 1998) and so are not included here. Stars in the next lower mass bin, 4.8–6.3 $M_\odot$, are not included because incompleteness for this mass bin are 68%–92% in the burst region.

As suggested by Scalo (1986), we only include stars on the main sequence, which we take to be $(V-I)_0 \leq 0.24$. Stars with masses 6.3–18 $M_\odot$ remain at $(V-I)_0 < 0$ while on the main sequence, but we take a larger color swath here to allow for uncertainties in the photometry of the colors and reddening corrections and to include the entire blue plume.

We must determine the relationship between mass and M_V for the limits of our mass bins. Since M_V varies as a star evolves even while the star is in its hydrogen-burning phase, we determined a time-weighted M_V, but the time-scale that we average over depends on our assumptions. Stars with masses 6.3–18 $M_\odot$ have hydrogen-burning lifetimes of 11 to 62 Myr. For the case of coevality, we assumed that the star formation took place over a time period $\leq$13 Myr, the lifetime of the average mass in the top mass bin. Therefore, to convert M_V to mass, we have used M_V averaged over 13 Myr. This should then fairly reflect the average M_V that we would expect for a given mass under our assumptions. The adjustment from zero-age M_V to average M_V is 0.6 magnitude brighter for 18 $M_\odot$ and decreases with decreasing mass (increasing lifetime).

For the case of constant star formation, we assumed that the age of the region T_0 is 40 Myr and that star formation has taken place at a constant rate there since then to the present. The choice of 40 Myr is motivated by the CMDs in which we see a strong blue main sequence as well as red supergiants on isochrones consistent with ages of up to 40 or 50 Myr. Ages of clusters, discussed below, are also consistent with this. In the constant star formation case we must multiply the mass function by $T_0/\tau_{ms}(m)$ in order to account for those stars that have died more than $\tau_{ms}(m)$ ago. We determine the average M_V over the hydrogen-burning lifetime for each mass limit. The exception is the lower mass limit of the lowest mass bin; the hydrogen-burning lifetime of a 6.3 $M_\odot$ star is 62 Myr, which is longer than T_0, so we average M_V over T_0 rather than 62

Myr.

The IMFs for these two cases are shown in Figure 8 and given in Table 1. The resulting Γ are -1.9 ± 0.4 under the assumption of coevality and -0.9 ± 0.3 under the assumption of constant star formation for $Z = 0.004$. Using $Z = 0.008$ stellar evolutionary tracks yields Γ of -2.1 ± 0.4 and -1.0 ± 0.04, respectively, nearly the same within the uncertainties. The real situation must lie between these two extremes. For comparison a Salpeter (1955) slope is -1.3. Thus, in the case of coevality, the IMF is steeper than Salpeter (fewer higher mass stars relative to lower mass stars), and in the case of constant star formation, the IMF is shallower than Salpeter. However, the uncertainties and likelihood of the true IMF lying between these two extremes do not rule out the IMF being the same as that measured by Salpeter. It seems likely, therefore, that the IMF of the intermediate mass stars formed in the starburst is not very unusual compared to what is found in most other populations.

4.2. Underlying Galaxy

We have also measured the IMF for stars in the region outside of the burst under the assumption that the galaxy there has undergone constant star formation for at least the past 100 Myr, the hydrogen-burning lifetime of 4.8 $M_\odot$, our lower mass limit. We included the mass bin 4.8–6.3 $M_\odot$ here, because in the underlying galaxy the incompleteness factors for this mass bin are lower than they were in the starburst region, 57%–67%. Because we are dealing with the constant star formation case, we must multiply the stars counted by $T_0/\tau_{ms}(m)$ in order to account for stars that have died longer than $\tau_{ms}(m)$ ago. We take T_0 to be 10 Gyr although, because T_0 is a constant in the IMF, the particular age chosen is irrelevant to determining the slope of the IMF. Again, we determine the time-weighted average M_V of each mass bin limit over the hydrogen-burning lifetime of each mass. We considered the regions in WF2 and WF3 not included in the starburst (see Figure 5). The area included is equivalent to a square 375 pc on a side. To remove foreground stars, we used the Bahcall-Soneira model as described above.

The IMF for the non-burst region is shown in Figure 9 and given in Table 1. Γ is -2.6 ± 0.3 for 4.8–18 $M_\odot$ for $Z = 0.004$. Using $Z = 0.008$ stellar evolutionary tracks yields a Γ of -2.3 ± 0.3. This is considerably steeper than the Salpeter (1955) function that is commonly measured in stellar clusters and associations in a wide variety of galaxies. The deviation is in the sense of fewer higher mass stars for a given number of lower mass stars. However, slopes this steep have been measured in a few situations: The slope is similar, within the uncertainties, to the slope measured for the starburst region in IC 10 under the assumption of coevality. It is also similar to the slopes measured by Massey et al. (1995b) for field populations of massive stars in the LMC, SMC, and Milky Way analyzed in the same manner.

If the star formation history of the underlying galaxy has been episodic over the past 100 Myr rather than constant, from the paucity of bright blue stars and red supergiants, we would

guess that the last burst must have ended of order 20 Myr ago. This corresponds to the main sequence lifetime of an 11 $M_\odot$ star. If we eliminate bins for masses greater than 10.7 $M_\odot$, the IMF becomes even steeper although uncertainties are large. Thus, the unusual character of the IMF remains.

5. Lower Stellar Mass Limit

We measure the IMF to 6.3 $M_\odot$ in the starburst region. Thus, the lower stellar mass limit is $\leq$6.3 $M_\odot$, which corresponds roughly to a B3V star. We detect stars down to 4.8 $M_\odot$ (B5V), but incompleteness is so high in the 4.8–6.3 $M_\odot$ mass bin (68%–92%) that detetermining numbers of stars is too uncertain to say whether they are there in normal proportions. The constraint of $\leq$ 6.3 $M_\odot$ is less than the 10–20 $M_\odot$ that is suggested for some systems from integrated measurements (for example, Augarde & Lequeux 1985, Olofsson 1989) and from theory (Silk 1986), but lower than others (for example, Rieke et al. 1993, Wright et al. 1988).

6. Wolf-Rayet Stars and the Unusually high WC/WN ratio

Massey & Armandroff (1995) surveyed IC 10 for WR stars and found an unusually large ratio of WC-type stars to WN-type stars. The WR stars represent an evolutionary phase in the life of massive stars where strong mass loss has laid bare nucleosynthesis products: helium and nitrogen in the case of WN stars and carbon and oxygen in the case of WC stars. Recently, Royer et al. (2001) have also surveyed IC 10 for WR stars and detected 13 new WR candidates. If confirmed with spectroscopy, 8 of the new WR stars would be of the WC type, and so the abnormally high WC/WN ratio will likely remain.

The WFPC2 field of view of IC 10 includes 6 of the 10 WC stars and 3 of the 5 WN stars, as well as one of the WN candidates, identified by Massey, Armandroff, & Conti (1992). The final list of WR stars and their coordinates is given by Massey & Johnson (1998). The field also contains 6 of the new WR candidates of Royer et al. (2001). The WR stars and candidates are marked on Figure 5, although the Royer et al. candidates numbered 11 and 12 do not correspond to any star in our image. All but one WR star, found in WF2, are located within the region taken as the burst region. Only one is located in close proximity to an obvious grouping of stars (cluster 2–1).

The WC/WN ratio of 2 found in IC 10 is 20 times too high for the galaxy's metallicity (Massey 1999). Massey & Armandroff (1995) had suggested that the starburst in IC 10 may have an IMF that is skewed towards the highest mass stars although the IMF would have to be extraordinarily peculiar to alone explain this ratio. Recently the work by Massey, Waterhouse, & DeGioia-Eastwood (2000) has shown that the same mass range contributes stars to the WC and to the WN type. However, if the time spent in the WC phase increases with mass, as expected, the unusual WC/WN ratio could still be due to the stellar IMF. However, to be explained in

this fashion, there would have to be more of, say, 100 $M_\odot$ stars than 40 $M_\odot$ stars. That is, the IMF slope, if the IMF was still a power law, would have to be positive, not negative. Thus, the IMF that we have found for the intermediate mass stars, if it extends to high mass stars, is not extraordinary enough to explain the observed WC/WN ratio.

Massey & Johnson (1998) suggest that one explanation for the unusually high WC/WN ratio in IC 10 could be that the mixed-age assumption in the empirical relationship is violated in IC 10. The empirical relationship shows WC/WN versus O/H for galaxy-wide counts, and the assumption is that star formation has been constant on a galaxy-wide scale in all these galaxies. On the other hand, if a galaxy population is highly coeval, as it might be in a starburst, the WC/WN ratio reflects the time since the burst occurred.

This has been quantified nicely by Schaerer & Vacca (1998) who show the evolution of WC and WN fractions with time for an instantaneous burst of star formation. For $Z = 0.004$, close to the $Z = 0.005$ expected for IC 10, the WC/WN ratio is greater than 1, and in fact about 2, 3–4 Myr after the burst. However, this would require that the burst in IC 10 be only 3–4 Myr old everywhere in the galaxy since the WR stars are found over a large region. This seems unlikely given the large number of red supergiants that are seen in the CMD (Figure 6); an age or burst duration of several tens of millions of years seems more likely.

However, Figure 9 of Schaerer, Contini, & Kunth (1999) is also suggestive. They have computed the expected WC/WN ratio for an instantaneous burst, bursts of several Myr in duration, and constant star formation, including several metallicities and both standard and high stellar mass loss. For the standard mass loss and $Z = 0.004$ the highest WC/WN ratio attained is only 0.3 and then only for a very short period of time. The longer the burst duration, the lower the peak ratio, and the WC/WN ratio for constant star formation is 0.04. Clearly these values fall far short of what is observed in IC 10.

However, the stellar evolutionary models with high mass-loss can produce much higher WC/WN ratios. Again, the instantaneous burst and constant star formation models only produce ratios of order 2 for ages 3–4 Myr. The constant star formation model settles down to WC/WN of order 0.5 after 4 Myr. However, the uncertainty in the measured WC/WN ratio in IC 10 is such as to allow a value of 1 (Massey 1999), and Massey & Johnson (1998), as well as Royer et al. (2001), suggest that incompleteness in the WN count is a possibility. If the true WC/WN ratio in IC 10 were closer to 1, the high stellar mass loss models with constant star formation might nearly predict what is observed. However, this is a circular argument because mass-loss rates are related to the metallicity of the stars. So, we would require that the stars in IC 10 have unusually high mass-loss rates for their metallicity compared to the other galaxies that define the metallicity–WC/WN relationship. There is no reason to expect this to be the case.

More likely, the WC/WN ratio is high because of a narrow range in ages as shown by Schaerer & Vacca (1998). The ratio could be reproduced if the bulk of the starburst occurred some tens of millions of years ago, there was a gap in star formation until recently, and then scattered pockets

of star formation 3–4 Myr ago produced the WR stars that we see now. This is also suggested by Royer et al. (2001). In this scenario the numerous red supergiants were produced in the older burst and are decoupled from the production of the WR stars that we see today. This does require, however, a highly synchronized second burst ($\Delta\tau \leq$1 Myr) in small pockets scattered over a large region of the galaxy. In terms of the IMFs computed in §4.1.2, these pockets are too small to contribute significantly to the star counts of the starburst region as a whole.

7. Star Clusters

7.1. Identification

We have examined the WFPC2 images for star clusters or distinct associations. In particular we were looking for objects that might be comparable to super star clusters, such as R136 in the LMC, or the smaller but more common populous clusters, also found in the LMC. R136, for example, has a half-light radius $R_{0.5}$ of 1.7 pc (Hunter et al. 1995), which would be 0.4″ at the distance of IC 10. Thus, a cluster like R136 would not be distinguishable from a star in ground-based images, but in *HST* images the $R_{0.5}$ of R136 would be 8 pixels in PC1 and 4 pixels in the WF CCDs, easily distinguishable from a stellar profile. Therefore, to search for compact clusters, we looked for anything that was resolved relative to a stellar profile. We also looked for less compact clusters or associations. Because of the starburst, however, much of the galaxy looks like an OB association. We looked only for those associations that appeared as distinct clumpings of stars. In what follows we will frequently refer to both clusters and associations that we identified as "clusters." We initiated our search on the F555W images, but then compared that image to F336W and F814W. However, we did not restrict ourselves to blue clusters, and the reddest clusters do not show up on the F336W image.

We identified 3 bright, blue star clusters and 1 faint, red cluster in the PC1 image; two clusters in WF2; and 7 clusters in WF4. No clusters were identified in WF3. The clusters are outlined in Figure 5 and their properties are given in Table 2. We identify the clusters with a number with two parts: the leading part is the number of the CCD that the cluster is found on and the following part is a running number to uniquely identify the cluster on that chip.

The clusters have half-light radii $R_{0.5}$ of 1.5–6.6 pc and M_V of −6.6 to −10. Clusters 4–7 and 4–8 are identifiable as resolved objects, but they are saturated in the F555W and F814W images and so have no photometry or $R_{0.5}$ listed in Table 2 and cannot be discussed further.

7.2. Integrated Colors and Magnitudes

The integrated colors and magnitudes of the clusters are given in Table 2. The clusters are also plotted in color-color diagrams and CMDs in Figures 10 and 11. In the Figures we also plot

cluster evolutionary models for Z of 0.008 and 0.004 and a Salpeter IMF (Leitherer et al. 1999). Ages along the evolutionary tracks of 1–9 Myr in steps of 1 Myr are marked with x's and ages of 10, 20, and 30 Myr are marked with open circles. The cluster evolutionary tracks end at 1 Gyr. Although a Z of 0.004 is closer to the expected metallicity of IC 10, the $Z = 0.008$ track appears to follow the observed colors better in Figure 10. In particular cluster 1–1 lies close to the evolutionary cluster track of $Z = 0.008$ and far from that of $Z = 0.004$. Better agreement of integrated cluster colors with a higher metallicity evolutionary track was also the case for clusters in NGC 1569 (Hunter et al. 2000) and in NGC 4449 (Gelatt, Hunter, & Gallagher 2001).

Of the clusters with measureable F336W, inferred ages span a range from 3–4 Myr to about 30 Myr, allowing for the uncertainties, and so they were probably produced in the starburst. Cluster 2–1 has an uncertain $(U-V)_0$ that could formally allow an age of $\sim$7 Myr to 200 Myr. However, it contains a WR star (Figure 5) and so must be young. In addition to the uncertainties in the photometry, however, there is also considerable uncertainty in determining ages of small clusters from integrated photometry because of the statistical effects of a few stars entering and leaving particular evolutionary stages. However, for those clusters large enough spatially to be resolved into individual stars, the integrated colors are consistent with the ages derived from CMDs. CMDs of two resolved clusters are presented in the next section.

Clusters 1–4 and 2–2 are red and do not appear in Figure 10 because F336W was not detected. However, they do appear in the bottom panel of Figure 11. Given that F336W was not detected, we estimate that $(U-V)_0 \geq 0.2$. From this and the observed $(V-I)_0$, we conclude that the ages of 1–4 and 2–2 are likely $\geq$350 Myr and could be as high as 1 Gyr since the clusters sit near the end of the cluster evolutionary track.

The cluster evolutionary tracks in Figure 11 are for a cluster mass of 3.3×10^5 M$_\odot$. For less massive clusters the tracks in Figure 11 would slide vertically to fainter M$_V$. We can see that, if the ages are correct, most of the clusters in IC 10 have masses of a few thousand M$_\odot$ or less and are, in fact, very small clusters or associations. The young clusters 4–1 and 1–2 and the old clusters 1–4 and 2–2 could have masses as high 10^4 M$_\odot$. This mass would still be small compared to that of a globular cluster or super star cluster, but perhaps not too much smaller than smaller populous clusters in the LMC. For example, the populous cluster NGC 1818 in the LMC has a total mass determined from star counts at 20 Myr and then integrated from 0.1 to 100 M$_\odot$ of 3×10^4 M$_\odot$ (Hunter et al. 1997).

The spatial distribution of star clusters can be seen in Figure 5. The youngest clusters (4–1, 4–2, 4–5, 2–1) are primarily located in the upper left corner of WF4, in the region with the most nebular emission. The exception is cluster 2–1 that is potentially only a few Myr older and is located along the right edge of WF2. The rest of the young clusters are arrayed around 4–1, 4–2, and 4–5, to the lower right and in the PC1, and have ages of order 15–30 Myr. Although invoking propagating star formation is tempting, we cannot in all honesty say that this arrangement necessarily implies causality between regions.

7.3. Resolved Clusters

The CMDs of clusters 1–1 and 4–1 are shown in Figures 12 and 13. Comparison with isochrones suggests that cluster 1–1 could be 15–20 Myr old. The integrated colors suggest an age of 10–14 Myr, so the two ages agree at an age of about 15 Myr. Cluster 4–1 appears to be as young as 4 Myr, and the integrated colors also indicate an age of 3–4 Myr.

For cluster 4–1 we have determined the richness (number of stars) and spatial concentration (number of stars formed per unit area) of stars with $M_V \leq -4$, in other words all massive stars. Star counts determined within the cluster boundary were corrected for incompleteness and contamination by foreground stars (which is <0.2 star in each magnitude bin under consideration). In Figure 14 we compare this cluster with other clusters of similar age. We see that cluster 4–1 is comparable to an OB association. It is not as concentrated or as rich as a super star cluster, as exemplified by R136 in the LMC, by several orders of magnitude. In fact, no cluster that we identified in the field of view of the *HST* images is comparable to a super star cluster.

8. Hα Shells

Figure 15 is a mosaic of the Hα CCD images with stellar continuum subtracted to leave just nebular emission. One can see that there is a considerable amount of Hα emission with a complex pattern of filaments in WF4. This emission indicates that it is here that the most recent star formation has taken place. The H II regions are numbered and catalogued by Hodge & Lee (1990).

A large shell dominates the Hα image and is seen in the upper left corner of WF4. This is shown more clearly in Figure 16 where the Hα image is superposed on the F555W image for the WF4 CCD only. The large shell is number 111 in Hodge & Lee's (1990) catalog. Cluster 4–1, outlined in the Figure, is located along the upper edge of this shell, where the Hα emission is strongest. Cluster 4–2 is located towards the center of the shell. The CMDs and integrated colors of these clusters indicate ages of a few Myr for both. The Hα shell is $9.7''$, or 45 pc, in diameter. If the ambient gas density n_0 is 1 cm^{-3}, a single massive star could easily blow a hole this size in a few Myr (Weaver et al. 1977, McCray & Kafatos 1987), so there is no problem producing this shell with stars in clusters 4–2 or 4–1.

To the lower right of this shell in Figure 16 are bright arcs of Hα emission. Cluster 4–4 sits near the center of curvature of several of these arcs (H II number 106 in Hodge & Lee 1990) which together look something like a spiral galaxy. The distance from the cluster to the outer arcs is $5.4''$=25 pc. Cluster 4–4 has integrated colors that indicate an age of 20–30 Myr, and this may be an older shell in the process of breaking up. Another tiny shell is found to the right of cluster 4–3 (H II number 98 in Hodge & Lee 1990). That shell is centered on a star and has a radius of $1.68''$=8 pc.

Thus, we find that in Hα the shells are quite modest. This implies that in this part of the

starburst region there are no super shells nor is blowout of gas from the galaxy likely (but see Hunter et al. 2001 for other parts of the galaxy).

9. The Mode of Star Formation in the Starburst

From the discussion in the previous sections we see that, in terms of star clusters, the starburst in IC 10 has not produced super star clusters but rather normal OB associations and small compact clusters. Only two of the young clusters may be comparable to smaller populous clusters such as are observed in the LMC. By contrast, the starburst in NGC 1569 has produced two super star clusters (see, for example, O'Connell, Gallagher, & Hunter 1994) and that in NGC 4449 has produced several as well (Gelatt et al. 2001). Yet, IC 10 is not unique in being a region of intense star formation and not producing super star clusters: the Blue Compact Dwarf galaxies IZw18 (Hunter & Thronson 1995) and VIIZw403 (Lynds et al. 1998) also have produced only scaled-up OB associations. Clearly, not all starburst events produce super star clusters even if giant H II regions are present (see also Kennicutt & Chu 1988), and the star formation process in IC 10 has been similar to that in IZw18 and VIIZw403 in terms of cluster production.

In the case of IC 10, the primary mode of star formation during the starburst appears to have been that of an OB association. Here we use the phrase "mode of star formation" to mean the primary units of star formation. The region identified as the burst region in Figure 5 is similar to an OB association in the distribution of stars. This is seen in Figure 17. This plot is similar to Figure 14 in which we plotted the richness of stars in cluster 4–1 against the spatial concentration of those stars. In Figure 17 instead we plot the richness versus the spatial concentration for stars in the burst region as a whole. In addition, we count stars with masses 6.5–15 $M_\odot$ rather than stars with $M_V < -4$. The advantage of counting stars in this mass range rather than to a brightness limit is that one can compare regions that are not the same age. The only requirement is that the regions be younger than the hydrogen-burning lifetime of the upper mass limit, here a 15 $M_\odot$ star—about 13 Myr, or that we can reasonably correct for stars that have evolved off the main sequence, as for NGC 1818, which is shown for comparison in the figure. For IC 10 we have counted stars 6.3—18 $M_\odot$, corrected for incompleteness and foreground stars, and scaled to 6.5—15 $M_\odot$ using the observed mass function. The IC 10 burst region is compared to other star-forming regions in the figure.

From Figure 17 we see that the spatial concentration of stars in the IC 10 burst region is that of a typical OB association seen in the Milky Way and LMC, but the numbers of stars are up by a factor of 40–400 compared to OB associations. These stars are located over a region equivalent to a square with a side of 425 pc or a circle with radius 240 pc. In fact, the mode of star formation in IC 10 is similar to that in the bulk of the stars in Constellation III in the LMC (labelled "ConIII-field" in the Figure). Constellation III is a large region that formed stars 12–16 Myr ago (Dolphin & Hunter 1998). The stars have now carved a hole out of the neutral gas that is $\sim$1 kpc in diameter (Dopita, Matthewson, & Ford 1985). In Constellation III there

are several compact clusters, but the bulk of the stars that formed in what was certainly a major star-forming event formed in the more diffuse distribution of an OB association. This appears to be the situation in the IC 10 starburst as well. The numbers of stars formed is also similar between the region surveyed by *HST* in IC 10 and the region surveyed from ground-based observations in Constellation III by Dolphin and Hunter. Both Constellation III and the starburst region surveyed in IC 10 cover roughly the same fractional area of their respective galaxies. Besides the similarity with Constellation III, IC 10's mode of star formation—that of OB associations—is like those in the two Blue Compact Dwarfs IZw18 and VIIZw403 (Hunter 1999).

10. Summary

We have presented *HST* U, V, I, and Hα images of the peculiar Local Group irregular galaxy IC 10. The images are used to determine the nature of the stellar products of the recent starburst in this galaxy. From these products we have probed the star formation process of the starburst itself. The starburst is explored through a region of the galaxy equivalent to a square with a side of 425 pc. The region outside of this is taken to represent the underlying galaxy population.

We assumed a single reddening of E(B−V)= 0.77 and found that this gave CMDs that compare well to isochrones. From the TRGB, we deduced a true distance modulus of 24.95±0.2, thus reproducing the reddening and distance combination of Massey & Armandroff (1995).

We identified 13 stellar associations and clusters in the *HST* images. Two of these are red and presumably old ($\geq$350 Myr). Integrated colors and CMDs suggest ages of 4–30 Myr for the rest and these were presumably formed in the starburst. The youngest associations and clusters are located in the strongest part of the nebulosity; the older clusters are located around the younger ones and within the starburst region.

The answers to the questions that we posed in the Introduction are as follows:

First, what is the stellar IMF of the intermediate mass (6.3–18 M$_\odot$) stars produced in the starburst? We determined the IMF for two limiting cases. Under the assumption that the starburst was highly coeval and took place no more than 13 Myr ago, the slope of the IMF is -1.9 ± 0.4. Under the assumption of constant star formation over the past 40 Myr, the slope is -0.9 ± 0.3. The true case is expected to lie somewhere between these two limits. These are calculated using $Z = 0.004$ stellar evolutionary tracks, which is close to the observed metallicity of IC 10. For $Z = 0.008$ tracks, which fit the location of the red supergiants better, Γ is -2.1 ± 0.4 and -1.0 ± 0.04, respectively, for coeval and constant star formation. Thus, most likely, the IMF of the intermediate mass stars is not very unusual. We also measured the IMF for the underlying galaxy population under the assumption of constant star formation for more than 100 Myr. We found a slope of -2.6 ± 0.3 for 4.8–18 M$_\odot$ assuming $Z = 0.004$ (-2.3 ± 0.3 for $Z = 0.008$) which is unusually steep compared to values measured in most circumstances in other galaxies.

Second, what is the lower stellar mass limit of stars produced in the recent starburst? The lower stellar mass limit is $\leq$6.3 $M_\odot$ because we measured stars in relatively normal proportions to this limit. This is an upper bound to the lower stellar mass limit; we are constrained in pushing this bound lower by the signal-to-noise of the data. This constraint is less than some predictions of what lower stellar mass limits might be in starbursts, but higher than others.

Third, what kinds of star clusters have been produced in the starburst? We found a few distinct OB associations and small compact clusters. There are no super star clusters in the *HST* field of view such as have formed in the starburst in NGC 1569. At most, a few of the clusters may be comparable to small populous clusters in the LMC.

Fourth, how does the nebular emission relate to the stellar products? There is a lot of filamentary structure in the Hα image, but only two modest-sized shells ($\sim$50 pc diameter). The shells are centered on star clusters/associations that could easily have produced them in the past few Myr. There is not evidence in this part of the starburst for super shells or blowout activity.

Fifth, what has been the mode of star formation in the starburst? By mode, we mean richness and concentration of the stars that have formed. The dominant mode of star formation has been that of a scaled-up OB association. That is, the spatial concentration is like that of an OB association, but altogether several orders of magnitude more stars have been formed in IC 10 than one finds in typical OB associations. This modest mode of star formation, with a few compact clusters sprinkled in, is similar to the star formation that took place in Constellation III in the LMC, as well as in the Blue Compact Dwarfs IZw18 and VIIZw403.

We also compare the high WC/WN ratio observed by Massey & Armandroff (1995) in IC 10 to evolutionary models of Schaerer & Vacca (1998) and Schaerer et al. (1999). We suggest that the high ratio can be reproduced if there were small, well-synchronized ($\Delta\tau \leq 1$ Myr), but widely scattered, pockets of secondary star formation 3–4 Myr ago.

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Fig. 1.— The field of view of the *HST* WFPC2 images of IC 10 is shown superposed on a ground-based V-band image of the galaxy kindly supplied by P. Massey. The field of view of the ground-based image is $14.3'$.

Fig. 2.— I-band color-magnitude diagram of stars in the non-burst portions of WF2 and WF3 taken to define the underlying stellar population. The magnitude and color have been corrected for reddening, as discussed in the text. Stars to the right of the dashed line, which include the RGB and AGB, were used in determining the I-band luminosity function. The solid, horizontal line is the apparent magnitude that we determined for the TRGB.

Fig. 3.— I-band luminosity function, where the I magnitude has been corrected for reddening. Stars were binned in 0.2 magnitude bins. The solid-lined histogram is the counts corrected for incompleteness and foreground stars. The other histogram is the counts before any corrections were applied. The short vertical line at I_0=20.8 marks what we took to be the TRGB.

Fig. 4.— Representative incompleteness fractions for star counts in M_V bins used in §4.1, §4.2, and §7.3. These fractions are for main sequence stars, taken to be stars with $(V-I)_0 < 0.24$.

Fig. 5.— Region assumed to have engaged in the recent starburst is outlined on a mosaic of the F555W *HST* images. The region consists of the PC1, most of WF4, and portions along the right edge of WF2 and WF3. The CCDs are identified in their corners. The rest of the field of view was used for subtracting the underlying stellar population from the burst. The large dust cloud in WF4, outlined with a box, was not used in either category. Star clusters and associations are circled and labeled. The size of the circle is what is taken to be the maximum extent of the cluster. Unlabeled circles indicate WR stars identified by Massey, Armandroff, & Conti (1992). The double circles are positions of WR candidates from Massey & Johnson (1998) and Royer et al. (2001) although two of the Roye et al. candidates (one in PC1 and one in WF4) do not correspond to obvious stars in our images.

Fig. 6.— Color-magnitude diagram of stars in the starburst region outlined in Figure 5. The uncertainties in the photometry are shown vertically along the left edge of each panel for selected M_V except where the uncertainties are smaller than the symbols. Isochrones for $Z = 0.004$ from Lejeune & Schaerer (2001) are shown for selected ages which are identified in units of Myr. The broadening in $(U-V)_0$ at faint M_V in the right panel is assumed to be partially due to red leak in the F336W filter that was not properly accounted for.

Fig. 7.— Color-magnitude diagram of stars in the underlying galaxy. The region is outlined in Figure 5. The uncertainties in the photometry are shown vertically along the left edge of each panel for selected M_V except where the uncertainties are smaller than the symbols. Isochrones with $Z = 0.004$ from Lejeune & Schaerer (2001) are shown for selected ages which are identified in units of Myr.

Fig. 8.— Stellar IMF shown for the starburst region minus the underlying galaxy. The IMF

is determined for two assumptions about the star formation history of the burst: coevality and constant star formation. For coevality we require the star formation activity to have taken place over a period of time shorter than the hydrogen-burning lifetime of the most massive mass bin being considered, 13 Myr. For constant star formation, we assume that stars formed continuously over the past 40 Myr.

Fig. 9.— Stellar IMF shown for the non-starburst region. Foreground stars have been removed using the Bahcall-Soneira model as described in the text. We assume constant star formation over at least the past 100 Myr, the hydrogen-burning lifetime of the lowest mass bin, and an age of the galaxy of 10 Gyr.

Fig. 10.— Integrated photometry of star clusters shown in a U, V, and I color-color diagram. The solid curve in the upper panel is an evolutionary track for a cluster with instantaneous star formation, a metallicity of $Z = 0.004$, and a Salpeter (1955) stellar IMF with an upper limit of 100 $M_\odot$ (Leitherer et al. 1999). The solid curve in the lower panel is the same models for a metallicity of $Z = 0.008$. Ages 1–9 Myr in steps of 1 Myr are marked with x's along these lines; ages 10, 20, and 30 Myr are marked with open circles. The cluster evolutionary tracks end at 1 Gyr. The arrow in the lower left corner of the upper panel is a reddening line for a change of 0.2 in $E(B-V)_t$. It represents the average of an O6 and a K5 type spectrum with $A_V/E(B-V)=3.1$ and a Cardelli et al. (1989) reddening curve.

Fig. 11.— Integrated photometry of star clusters shown in U, V, and I color-magnitude diagrams. The solid curve is an evolutionary track for a cluster with instantaneous star formation, a metallicity of $Z = 0.004$, and a Salpeter (1955) stellar IMF with an upper limit of 100 $M_\odot$ (Leitherer et al. 1999); the dashed line is the same model for a metallicity of $Z = 0.008$. Ages 1–9 Myr in steps of 1 Myr are marked with x's along these lines; ages 10, 20, and 30 Myr are marked with open circles. The evolutionary tracks end at 1 Gyr. The evolutionary tracks are those for a mass of 3.3×10^5 $M_\odot$; for other masses the lines would slide vertically in the diagrams.

Fig. 12.— Color-magnitude diagram of resolved stars within a radius of $1.96''$ (=9 pc) from the center of cluster 1–1. The overplotted lines are $Z = 0.004$ isochrones from Lejeune & Schaerer (2001); the numbers that label the lines indicate ages in Myr.

Fig. 13.— Color-magnitude diagram of resolved stars within a radius of $3.09''$ (=14 pc) from the center of cluster 4–1. The overplotted lines are isochrones from Lejeune & Schaerer (2001); the numbers that label the lines indicate ages in Myr.

Fig. 14.— Number of stars with M_V brighter than -4 versus the spatial concentration of those stars in IC 10's cluster 4–1 and other young regions. Except for NGC 206, a region in M31 with an age of roughly 6 Myr (Hunter et al. 1996b), most of the regions listed are similar in age to IC 10's cluster 4–1. Thus, we are comparing the number of massive stars formed in star-forming events of similar age. "MW,LMC OB" refers to OB associations in the Milky Way and LMC (Massey et al. 1995a,b); "R136" is a super star cluster in the LMC (Hunter et al. 1995). Two regions are shown

in each of the Blue Compact Dwarfs IZw18 (Hunter & Thronson 1995) and VIIZw403 (Lynds et al. 1998). Data for NGC 604, a giant H II region in M33, are taken from Hunter et al. (1996a).

Fig. 15.— Mosaic of the 4 Hα WFPC2 images. Stellar continuum, formed from F555W and F814W, has been subtracted to leave just nebular emission.

Fig. 16.— WF4 image. F555W is shown in black with F656N (Hα) subtracted in order to superpose the Hα as white. The star clusters are outlined and numbered. The positions of Brγ sources numbered 3—6 of Borissova et al. (2000) are circled and labelled "BR" followed by the number of the source in Borissova et al's Table 1.

Fig. 17.— Number of stars with masses 6.5—15 $M_\odot$ in the starburst region plotted against the spatial concentration of those stars. The burst region in IC 10 ("IC 10:burst") is compared to other young regions. "MW,LMC OB" refers to OB associations in the Milky Way and LMC (Massey et al. 1995a,b), and the horizontal dashed line extends the spatial concentration of typical OB associations across the figure for comparison. Data for R136, a super star cluster in the LMC, is taken from (Hunter et al. 1995); for NGC 206, an association in M31, from Hunter et al. (1996b); for NGC 604, a giant H II region in M33, from Hunter et al. (1996a); and for NGC 1818, a populous cluster in the LMC, from Hunter et al. (1997). "ConIII-cl" and "ConIII-field" are clusters and field stars in Constellation III in the LMC (Dolphin & Hunter 1998).

TABLE 1
Stellar IMFs

Mass ($M_\odot$)	M_V bin	log ξ log(Number/Δlog $M_\odot$)	$\sigma_{log\xi}$	Γ	σ_Γ
Burst region, coeval ($Z = 0.004$):					
6.3—8.2	−0.91 to −1.62	4.21	0.03	−1.95	0.39
8.2—10.7	−1.62 to −2.33	4.08	0.02		
10.7—13.8	−2.33 to −3.17	3.91	0.02		
13.8—18.0	−3.17 to −3.89	3.53	0.02		
Burst region, coeval ($Z = 0.008$):					
6.3—8.2	−0.99 to −1.68	4.20	0.03	−2.07	0.38
8.2—10.7	−1.68 to −2.43	4.08	0.02		
10.7—13.8	−2.43 to −3.26	3.86	0.02		
13.8—18.0	−3.26 to −3.98	3.49	0.03		
Burst region, continuous star formation ($Z = 0.004$):					
6.3—8.2	−1.20 to −2.07	4.27	0.02	−0.90	0.28
8.2—10.7	−2.07 to −2.68	4.03	0.02		
10.7—13.8	−2.68 to −3.29	4.04	0.02		
13.8—18.0	−3.29 to −3.90	3.93	0.03		
Burst region, continuous star formation ($Z = 0.008$):					
6.3—8.2	−1.27 to −2.04	4.24	0.02	−1.02	0.04
8.2—10.7	−2.04 to −2.78	4.10	0.02		
10.7—13.8	−2.78 to −3.38	4.00	0.02		
13.8—18.0	−3.38 to −3.98	3.89	0.03		
Underlying galaxy, continuous star formation ($Z = 0.004$):					
4.8—6.3	−0.82 to −1.44	2.05	0.02	−2.57	0.31
6.3—8.2	−1.44 to −2.07	1.75	0.04		
8.2—10.7	−2.07 to −2.68	1.22	0.07		
10.7—13.8	−2.68 to −3.29	1.15	0.09		
13.8—18.0	−3.29 to −3.90	0.88	0.14		
Underlying galaxy, continuous star formation ($Z = 0.008$):					
4.8—6.3	−0.92 to −1.53	1.96	0.02	−2.31	0.27
6.3—8.2	−1.53 to −2.13	1.63	0.04		
8.2—10.7	−2.13 to −2.78	1.22	0.07		
10.7—13.8	−2.78 to −3.38	1.05	0.10		
13.8—18.0	−3.38 to −3.98	0.93	0.13		

TABLE 2
Integrated Cluster Properties[a]

Cluster[b]	RA[c] (2000)	DEC)[c] (2000)	s[d] ($''$)	R[d] (pc)	$R_{0.5}$[e] (pc)	F555W	F336W−F555W	F555W−F814W	M_V	$(U-V)_0$	$(V-I)_0$
1-1	0 20 25.13	59 18 07.81	55	340	4.4	18.43	0.02	1.90	-8.90	-0.46	0.94
						0.00	0.03	0.00	0.00	0.03	0.00
1-2	0 20 24.62	59 18 12.53	52	340	1.6	18.67	0.09	1.60	-8.66	-0.47	0.63
						0.00	0.01	0.00	0.00	0.01	0.00
1-3	0 20 24.95	59 17 39.97	56	310	6.6	19.02	0.34	1.28	19.02	0.34	1.28
						0.00	0.00	0.00	0.00	0.00	0.00
1-4	0 20 23.92	59 17 45.29	47	260	3.2	20.69	...	1.82	-6.64	...	0.87
						0.01	...	0.02	0.01	...	0.02
2-1	0 20 26.90	59 18 17.22	70	450	4.8	20.28	0.69	1.44	-7.05	-0.01	0.48
						0.01	0.14	0.02	0.01	0.14	0.02
2-2	0 20 24.28	59 19 10.54	85	610	4.7	20.77	3.50	1.78	-6.56	...	0.82
						0.02	2.81	0.02	0.02	...	0.02
4-1	0 20 27.77	59 17 38.65	77	430	6.0	17.36	-0.44	0.91	-10.02	-1.25	-0.10
						0.00	0.01	0.01	0.00	0.01	0.01
4-2	0 20 28.16	59 17 35.63	79	460	3.7	19.94	-0.39	1.06	-7.45	-1.21	0.05
						0.01	0.03	0.02	0.01	0.03	0.02
4-3	0 20 26.58	59 17 02.53	87	420	1.7	19.44	0.04	1.22	-7.96	-0.87	0.21
						0.00	0.02	0.00	0.00	0.02	0.00
4-4	0 20 27.47	59 17 07.92	89	440	<1.4	19.87	0.12	1.35	-7.45	-0.47	0.38
						0.00	0.02	0.00	0.00	0.02	0.00
4-5	0 20 28.55	59 17 21.81	89	470	<1.4	19.39	0.32	1.06	-7.99	-0.66	0.05
						0.00	0.01	0.00	0.00	0.01	0.00
4-6	0 20 26.51	59 16 36.26	106	510	...	...	...	...	...	...	...
4-7	0 20 27.58	59 16 36.49	111	540	...	...	...	...	...	...	...

[a] The second row for each object contains the uncertainties in the photometry values in the preceeding row. U has been corrected for red leak in F336W.
[b] A leading "1" identifies PC1, "2" identifies WF2, and "4" identifies WF4.
[c] Units of RA are hours, minutes, seconds; and units of DEC are degrees, arcminutes, and arcseconds.
[d] s is the observed distance from the center of the galaxy in arcseconds; R is the distance in the plane of the galaxy in parsecs. R is determined using an inclination of 47° and a position angle of −49° for IC 10. These values were determined from the deep R-band ground-based image. The center of the galaxy, also determined from the ground-based image, is taken to be $0^h\ 20^m\ 18.06^s$, $59^\circ\ 17'\ 59.6''$ (epoch 2000). The distance to IC 10 is taken to be 0.95 Mpc.
[e] Radius that contains half the light of the cluster.

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